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Integrated Pest Management in the U.S.: Progress and Promise*

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In the U.S., where heavy use of insecticides has been commonplace for years, the development of proper integrated insect pest control cannot get underway unless there is a changed use pattern for such chemicals. A changed use pattern, however, cannot be accomplished without much study to establish the requirements for integrated control for each major crop situation. In this paper recent developments in a number of crop areas in the U.S. in which the necessary study has been begun are reviewed.

Important phases in the development of integrated control programs include: the single tactics phase, the multitactic phase, phase, the biological monitoring phase, the modeling phase, the management and optimization phase, and the implementation phase.

Several crops are discussed in relation to how far along we are in the development of practical programs of insect pest control. These are cotton, apples, alfalfa, soybeans, citrus, corn, cereal grains, tobacco and pine forests.

Several of these programs have already made substantial headway, e.g., those for cotton, alfalfa, apples, tobacco, and soybeans, although the accomplishments have not been even or parellel with respect to the phases of development where progress has been good.

The review of developments in these crops suggests that programs of control for individual crops and perhaps for complexes of associated crops will be developed according to specific needs of the crop, the geographic area and the pests, the technologies available and the socioeconomic and political factors of relevance. The tendency will be toward greater use of science in pest control decision-making, with extensive use of biological monitoring to establish realistic levels of threatened damage to the crop, and greater concern given to possible profit reductions and environmental disturbances of applying an insecticide, as well as the possible gain from doing so.

Introduction

In the last decade there has been much reappraisal of where we stand in pest control, particularly in insect pest control. The problem in this country is rather different from that of developing countries. Here, there already has been an extensive use of broad–spectrum organosynthetic insecticides which certainly gave striking results for many pests. However, detrimental side effects soon developed, including resistant types of pests and resurgence of target species, destruction of natural enemies and release of previously innocuous ones to pest status, residue and public health problems, and other more general environmental effects. These problems have been elaborated many times (*1–3*) and will not be dealt with here. In the developing countries, pests continue to take a significant part of the harvest, e.g., in South America, 33%; in Africa, 42%; in Asia, 43% (*4*), and not much is done to prevent it. Insecticides are not used extensively. Consequently pest control measures in these countries can be integrated to begin with; whereas in the U.S. we can only accomplish this by reducing and modifying the existing intensive and automatic use of insecticides so that alternative measures can have their potential effects. Here we must rethink and research our whole program of pest control in order to determine if a multifactorial approach (i.e., use of a combination of chemical, cultural, and biological strategies or tactics)

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can be used to reduce the heavy costs and detrimental effects of unilateral reliance on chemicals.

In the past decade, considerable effort has been expended in this country to do this. For example, in North Carolina, a significantly changed approach to control of insects and diseases of tobacco has been developed; the same is true in Washington for spider mites on apples. The concept of integrated control is not really new; it had an early proponent in Woodworth in the early 1900's (*5*), and later advocates were Pickett (*6*) in Nova Scotia and Michelbacher (*7*) in California.

In the past five years, an additional dimension has been added to the way we approach pest control problems. We are not yet sure what its ultimate impact will be, but it appears that the technology being developed will result in a greater integration of pest control with other aspects of agricultural management as the focus is properly placed on crop production. We are referring especially to the introduction of systems analysis and the computer science technology which is developing in relation to pest control research and making recommendations to pest managers. In developing this new technology, several efforts were simultaneously initiated. One has been concerned with cereal leaf beetles in Michigan (*8*); another with pests of cotton in Mississippi, Arizona, and Texas (*9,10*). Still another was the broader effort embracing not only cotton but five other crops, including alfalfa, stone and pome fruits, soybeans, citrus, and pine forests (bark beetles), initiated by the U.S./International Biological Program (IBP), funded by the National Science Foundation (NSF), the Environmental Protection Agency (EPA), and 18 participating universities, with some support by the USDA. The goals of this program have been expressed in different ways, but in general they are: to develop ecologically based and structured systems of management of pest populations at noneconomic densities so as to optimize economic returns on a continuing basis consistent with minimal environmental damage and to demonstrate that agricultural research can be done in a more productive way than in the past through unified, interdisciplinary approaches utilizing systems analysis.

These projects noted above and other related ones have provided a major thrust to the use of modeling as an important tool in structuring pest management research. The first goal expressed above for the US/IBP project would generally apply to the nationwide efforts underway to develop integrated pest management. In the remaining portions of this document the success achieved in attaining these goals and its probable impact in the future are discussed.

Progress in Integrated Pest Management

Entomologists have learned that an excellent way to estimate future trends in insect populations is to study the historical records of their population dynamics in the past. Perhaps also the future promise of integrated pest control in the U.S. can be estimated from reviewing its recent advances. In this paper, developments primarily in insect control for 9 crops are dealt with. Emphasis is placed on crops carrying heavy pesticide loads or those of great importance to food or fibre production. Each is considered in terms of three evaluation criteria. First, has the program resulted in increased *economic return to the grower (and/or to the consumer)* as contrasted to non-integrated control programs Second, has the program resulted in a reduction in the adverse influences of the pesticide program to the environment or public health and to what extent, contrasted to nonintegrated programs And last, has the program resulted in scientific and methodological advances by which its success can be measured.

In addition, several phases of development of an integrated control program, beyond those given by Smith (*11*), may guide us in judging advancement of a given program. These are: a single-tactic phase, a multitactic phase, the biological monitoring phase, the modeling phase, the management land optimization phase, and the systems implementation phase.

The single-tactics phase is somewhat of a "straw man" which is often associated with strictly calendar date spray programs, i.e., with nonintegrated pest control measures; it is not an actual phase in the development of an integrated control program.

The multitactics phase embraces the search for new tactics or strategies for controlling or manipulating insect populations, including cultural, mechanical, physical, biological, and regulatory measures (*1,2,12*). These tactics have received a great deal of attention following the recent emphasis of the integrated control concept.

In recent years, considerable attention has focused on developing more refined sampling and/or biological monitoring methods which allow pest control advisers and managers to determine more precisely the changes in the state of an insect, natural enemy or crop plant population, in relation to the need for applying a control measure and/or the best time to do so (i.e., economic damage levels, use of pheromone traps, and/or parasite-host or predator-prey ratios). Progress and interest in this phase is exemplified by the efforts of the Federal Extension Branch of the USDA to establish pest management scouting and advising systems for a variety of agricultural crops.

The modeling phase, as broadly defined, includes the conceptualization of a process by mental, pictorial, flowchart or mathematical means and has as its objective to understand, manage, or predict some feature or totality of the process in question. For prediction, there is of course a trade-off between monitoring the development of an insect, natural enemy, or crop population and forecasting its expected development based on simulation or mathematical models. The more one can predict, the less he needs to monitor and vice versa. Models, through sensitivity testing and validation, can also play an important role in elucidating control elements and critical parameters in a pest management system to which research can be directed.

As many individual components of a pest management system or beyond this, of a crop production system, are developed as subunits or submodels, they must be integrated or coupled into a total crop management system. This is the management and optimization phase. The difficulties of integrating such a complex of variables so that each can be managed in a way to give optimal benefits are apparent. For many years this type of integration has been carried out by intuitive experience gained from trial-and-error experimentation, but more recently, mathematically-based pest management models for entire complexes and techniques for economic analysis and optimization are also being used on a more quantitative basis.

In theory, the systems implementation phase is the culmination effort which concentrates or simplifies the best system of control methodologies and integrates monitoring, modeling and management tools into a system of delivery to the pest manager. Although effective systems can be based on traditional methods (i.e., off-line mode, without mathematical models) use of real-time weather acquisition systems which interface with biological monitoring systems (*8,13,14*) provide for rapid delivery of decision-making information to the pest manager, including feed-back data which provide up-dates on the state of the entire crop–pest system. Beyond the initial development, research in this phase is undertaken only when refinement or further improvements are needed in response to pest adaptations or changing crop technology. As indicated in the following discussion, for no crop have we reached this level of sophistication.

Cotton

Cotton is grown in the U.S. from California to the Carolinas and from the Gulf of Mexico northward as far as Illinois. Losses to insects exceed \$500 million annually and \$150 million is spent on insecticides, which is about 45% of the total used in agriculture. About 50% of the cotton acreage is not treated in most years. Thus the potential benefits to be derived from advanced pest management on this crop are substantial.

In general, three major cotton agroecosystems exist, and the insect pests for each case be characterized as follows (*15*): (1) the irrigated deserts of the Far West where the major pests are the pink bollworm, lygus, bollworm, and spider mites; (2) the semiarid regions of the Southwest where the bollweevil, fleahopper, bollworm, and tobacco budworm are the major pests; (3) the humid regions of the mid-South and Southeastern U.S., where the bollweevil, plant bug, bollworm, and tobacco budworm are the major pests.

In each of these cotton areas there is a major pest which must be controlled; there are also ones which appear to be largely pesticide-induced, and these can be avoided by properly chosen insecticide regimes or by use of other alternative methods.

In the 1950's and 60's, and even today, cotton insect control on substantial acreages has been and still is almost exclusively a single-tactic situation, i.e., a systematic application of insecticide every 5–7 days, according to Casey, Lacewell, and Sterling (*16*). These control programs were and are plagued with problems, including the development of resistance to the point of ineffectiveness for some species, environmental problems, and high costs for treatments in the face of a darkening economic picture for cotton production.

This situation, however, is rapidly changing and was changing even before the establishment of the NSF/IPM project or the USDA Extension Service Action programs which are also helping to alter this situation. Practical entomologists, extension people, consultants and supervised control specialists or "applied insect ecologists" had earlier developed practical programs, the latter by selling advice to growers. They made practical evaluations of the pest-crop system, pest occurrence, natural enemy presence, and probable impact on yield before advising use of chemicals; systems science in its limited technical usage had no part, but at the broader conceptual level it was involved, especially at the level of integration.

Recently there has been interest in developing new tactics for cotton insect control. Most of these

Table 1. Genetic sources of insect resistance found in cotton and currently being utilized in breeding programs (Texas, Mississippi, USDA and Cooperating States of Louisana and Missouri).[a]

Morphological or chemical characters identified	Resistance[a]					
	Boll weevil	*Heliothis* complex	*Lygus lineolaris* *Lygus hisperus*	Cotton fleahopper	Spider mites	Whiteflies
Frego	R(90–90% suppression)	N (insecticide coverage *increased)*	S	S	N	N
Nectariless	N	R (20–50% egg suppression)	R	R	N	N
Smoothleaf (glabrous)	N	R (60% egg suppression)	S	S	R–	N
High gossypol	N	R	N	R–	N	N
Pilose (Pubescence)	R–	S	R?	R	N	S
Okra leaf	N (Better insecticide coverage increased kill in squares)	N	N	N	N	R–
Red color	R(choice *situation)*	N	N	N	N	N
"X" Factor *(G. hirsutum* *wild races)*	N	R	N	N	N	N
Oviposition suppression factor *(G* hirsutum wild races	R (40% + suppression of egg)	N	N	N	N	N
Plant bug suppression factor (Stoneville, wild races and other sources)	N	N	R	R	N	N
G. barbadense (Pima S–2)	N	R–	N	N	R	N
Earliness of maturity	R (escape)	R (escape)	N	N	N	R?

[a]Data of Beck and Maxwell (*17*).
[b]R = resistant; N = no effect; S = increased susceptibility.

fall within the strategy of integrated control or pest containment. However, programs for eradication by initial, intensive use of insecticides, followed by massive release of sterile insects or use of other genetic eradication tactics, fall in the strategy of eradication and are outside the scope of this paper.

Work to develop varieties of cotton resistant to or tolerant of insect pests has been going on for some years; the NSF/IPM project has assisted to speed up and better coordinate some of this activity (Table 1). Different degrees of resistance to various cotton insects is afforded by lines possessing such characters as frego bract, glabrous, nectariless, pilose, high square gossypol, okra-leaf, and X-factor, and these traits are being incorporated into productive agronomic backgrounds. At least one nectariless variety has been released commercially (*18*).

The possible benefits from combined use of resistance, built into the new, smaller, short-season cottons, combined with crop residue destruction, are considerable. Various insect pests (and diseases) may thus be better managed or avoided and, moreover, costs for pesticides, labor, and fossil fuels would be much reduced (*19,20*). Nevertheless, the work has shown that certain problems will be difficult to overcome by breeding alone. For example, frego bract types are more resistant for weevil but more susceptible for plant bugs; glabrous types are more resistant for *Heliothis* but more susceptible for leafhoppers (*21,22*).

Natural enemies are important in cotton ecosystems, and the role of predators and parasites is being evaluated, as is the utility of microbial insecticides. There have been experimental efforts to suppress bollworms by mass release of *Trichogramma* and *Chrysopa* (*23*) and to increase the complement of natural enemies by introductions from Latin America (none yet successful).

Research has been done on both descriptive and predictive modeling for cotton. This started with models for the growth and development of a single cotton plant (*24,25*); they are now developed for a population of field plants and have been verified for three seasons in California (*26*). Workers in Mississippi, Texas, Arkansas, Arizona (*15*) and several other states (*9*, Colwick and H. D. Bowen, in press) have also reached high levels of attainment in plant and pest modeling. Submodels have been developed in the IPM project or are being developed for the following: leaf photosynthetic production (Texas) (*27*), drying of abscissed cotton squares (relative to mortality of boll weevils) (Texas), light penetration of row crops, such as cotton (Texas), drift of an insect pheromone (Texas), modified SIMCOT plant growth models (California, Texas, Mississippi), insect movement (North Carolina, Texas), bollworm ecosystem(s) (including one for natural enemies) for evaluation of alternative control tactics (Mississippi, Arkansas), natural enemies of bollworm (Arkansas), fleahopper dynamics (Texas), boll weevil (physiology and population dynamics) (Texas), pink bollworm and lygus bug dynamics (California), single-treatment, two-variable model for optimizing pesticide treatment (California) (*28*), addition of a nonlinear kill efficiency to the Hall and Norgaard model (Texas), economic thresholds and interfacing of plant growth and insect models (Mississippi) (*29*), an overview model of a cotton pest management system (Texas) (*30*).

In addition, various models have been developed or are being developed to deal with all aspects of cotton production from planting to harvest. For cotton pest management, however, all the submodels above have not been interfaced into a management decision model and, indeed, all of them probably will never be used in such a system. It will be necessary in developing practical (implementable) guidelines to simplify submodel elements to essential components, but this can best be judged after the necessary insight has been gained by simulation and validation studies.

With respect to implementation, use of a new integrated control strategy by the Texas Department of Corrections in cooperation with Texas A & M University, as a result of increasing pesticide resistance of the tobacco budworm, further substantiates that economic and environmental benefits may be gained by IPM approaches if adopted for cotton. The new program was: bollweevil control with a fall diapause program, fleahopper control with low dosages of insecticides applied early in the season, termination of fleahopper treatments quickly to allow natural enemies to build up and control bollworm and tobacco budworm populations, careful sampling, to initiate control techniques only after pest populations are determined to exceed economic thresholds, and harvesting of the crop and destruction of residuals as early as possible. Following use of this program in the Brazo River area, insecticide use declined from 12 to 6.4 lb/acre while lint yield increased from 229 to 345 lb, of which 50% was attributed to improved pest control. In the Trinity River region, insecticide use was reduced from 10.8 to 5.6 lb/acre and yields were increased by 80 lb/acre. Extrapolation of these effects to the 215,000 acres of cotton in this area suggests that annual insecticide use could be reduced by 1.4 million lb and cost benefits alone would increase by $5.4 million (*16*). Impressive statistics for the diapause bollweevil suppression program in the Texas High Plains (*31*) and the Mississippi scouting programs have also been attained, including a 50% reduction in insecticide usage.

In many areas, the introduction of real biological monitoring (as opposed to quasisampling provided by insecticide salesmen) in relation to evaluating economic thresholds and crop compensation capacities have provided for significant benefits (e.g., the state-supported "scouting" programs developed in Arkansas and the private advice of applied insect ecologists in California). These above programs have been improved by the IPM modeling efforts and when coupled with the biological monitoring programs described, they begin to approach the systems implementation stage.

Apples

The value of stone and pome fruits grown in the U.S. is well over $700 million annually. Losses from insects and mites average about 25% of this total and costs for pesticides are about 12% Among the pome and stone fruits, apples receive the greatest amounts of pesticides; they are only behind cotton and corn in total use and on a per acre basis they rate even higher.

Concerning methodological advances associated with apple pest control, development of alternative tactics for control of the direct fruit pests of this relatively stable crop are limited because cosmetic appeal is a significant feature and little damage is tolerated. By and large, insecticides are the principal measure used for direct pests (those attacking the fruits) of apple, although substantial reductions in pesticide usage have been achieved by improved pest monitoring techniques, and therefore better timing of applications and more precise appraisal of the need to spray. This has been greatly facilitated by the identification of sex pheromones and/or their synthetic mimics which have been made commercially available for such species as the codling moth, oriental fruit moth, red-banded leafroller, tufted apple budmoth and others. Pheromones of several apple pests (e.g., codling moth, red-banded leafroller) are also being experimentally evaluated as direct control measures in mass trapping and pheromone confusion studies.

Considerable success has been achieved in reducing the pesticide load and costs for control of several indirect pests which feed on the foliage or woody tree parts, including mites, scales and aphids. In Washington, integrated programs have achieved an approximate 50% reduction in the use of chemical pesticides (*32*) and in the midwestern and eastern U.S. where the pest complex is more varied a 20–30% reduction has been realized (*33*). The greatest success has involved the integration of biological and selective chemical control of plant-feeding mites (e.g., European red mite and McDaniel spider mite). Use of the coccinellid beetle, *Stethorus punctum*, and two phytoseiid mites, *Amblyseius fallacis* and *Typhlodromus occidentalis*, has been the basis of these programs. Their successful exploitation is largely due to the fact that each predator is either tolerant or has acquired high levels of resistance to organophosphate insecticides which are commonly applied for fruit pest control (*34*).

With respect to modeling, three prototype efforts are being conducted and coordinated throughout the major fruit producing states through the NSF/IPM program (*35*). A system of forecasting codling moth phenology based on pheromone trap monitoring and use of physiological-time modeling has been developed and validated, and is currently delivered to apple growers as a component of an on-line Extension Service delivery system in Michigan (*36*). Another direct fruit pest which is similarly being modeled is the tufted apple budmoth. Also, additional efforts to develop models for timing spraying for the codling moth (*37*) and predicting its population dynamics following sterile male release programs (*38*) in the western U.S. are almost completed.

A second important prototype modeling effort (for a disease) is in progress in New York, Michigan, and Pennsylvania for the key apple disease, apple scab. Submodels for this fungus which have been completed or are in progress include: a forecasting system for primary scab infection, an ascospore maturity submodel, a secondary lesion submodel, fungicide spray components, and lastly a total simulation for apple scab development—VISIM (*39*).

The third prototype modeling effort, in this case for a secondary arthropod pest of apple, is centered on plant-feeding mites and incorporates their key predators. Three institutions, Pennsylvania State University, Washington State University, and Michigan State University, are cooperatively involved. In Pennsylvania, a simulation model for the interaction involving the European red mite, its predator *S. punctum* and the acaricide-fungicide Dikar, has been developed, validated and is currently being used in a simplified form by fruit growers (*40*). In Washington, model development emphasizes the spider mite, *T. mcdanieli* and the phytoseiid predator *T. occidentalis*. In Michigan, European red mite and the predator *A. fallacis* are the prinicpal prey and predator species. In each of these studies, coupling of the respective pest and natural enemy submodels has been accomplished and model simulations provide outputs which predict whether biological control will be successful or if selective acaricides should be applied to establish more favorable predator-prey ratios.

As noted previously, employment of models in actual pest management programs for apples has been developed in both "off-line" and "on-line" modes. In Washington, Michigan, New York, and Pennsylvania, states that grow more than 70% of the U.S. apple crop, Action programs sponsored by growers and receiving Federal support are providing for rapid establishment of integrated control programs. In Michigan, models for control of codling moth, apple scab, and plant-feeding mites are being used presently as the focus or essential core of a pest management system for the whole complex of apple pests. Output recommendations from these models are delivered daily to Extension personnel via telecommunications lines to teletype terminals. This prototype pest management delivery system for apple pests utilizes on-line weather from 26

NOAA sites located throughout the Michigan fruit belt (*14*). It is part of a larger network embracing pest management for many crops (see discussion of cereal crops).

Alfalfa

Alfalfa in the U.S. is a major crop in its own right and is used primarily as a feed for domestic livestock. It is not a crop which receives large amounts of pesticide, but it does support a wide variety of insects including destructive species, pollinators and particularly beneficial natural enemies which overwinter or build up in alfalfa before migrating into neighboring crops. The point is that insects initially associated with alfalfa often affect associated crops (e.g., cotton, soybeans), and gives alfalfa pest management particular significance beyond that commonly ascribed to a single crop system.

Development of integrated pest control systems for alfalfa is among the most advanced in the U.S. This progress is due in part because this crop is grown in virtually every state and it has a single principal insect pest, the alfalfa weevil (or Egyptian alfalfa weevil) which is similarly distributed; it is also because the philosophy of integrated control has long been accepted by alfalfa entomologists (*41*) and extensive use of chemicals has simply been prohibitive from the point of view of cost. Researchers readily pooled their talents to develop integrated pest management programs and modeling expertise was incorporated at a very early stage (*35,42*). To date, the effective tactics for control of the alfalfa weevil have included cultural, chemical, biological, and host plant resistance means.

Integration of chemical, biological, and cultural methods for alfalfa weevil control is greatly dependent upon the biology and ecology of the respective weevil, its parasites, and the phenology of the plant's development. These features differ seasonally and from place to place. The tactics used range from spraying or cutting the alfalfa during early summer and thereby destroying the larvae or by doing the same in late fall so as to reduce the number of overwintering eggs laid in the southern states, to precisely timing the cutting of the first crop in the spring so that many of the weevil larvae and eggs are killed, and applying a stubble spray if needed after first harvest to clean up the remaining larvae in northern states (*42*). Inclusion of host plant resistance in integrated control programs for alfalfa insects, including the alfalfa weevil and especially for the spotted alfalfa aphid, has been substantial, but as yet multiple pest resistance has not been achieved to the extent that resistant varieties adapted to a wide range of cultural and climatic conditions are available. In recent years, biological control of the alfalfa weevil in most of the U.S. has been greatly increased by the establishment of several natural enemies, the most important being the larval endoparasite, *Bathypletes curculionis*, and the braconid, *Microctonus aethiops*, which attacks the adult weevil. In many areas, these natural enemies provide for significant control of the weevil, but in California the practical situation has drastically changed with the appearance and spread of the Egyption alfalfa weevil which is ineffectively parasitized by the former species.

Since rather refined manipulations of control measures (e.g., insecticides or cutting) in relation to pest, parasite, and predator numbers, damage potential, and crop development are critical to achieving optimal pest control,the application of system science technology was a natural research development that was begun about 4 years ago.

Models for the growth dynamics of alfalfa under California (Gutierrez et al. in press) and midwestern-eastern nonirrigated conditions (*43*, Ruesink, in press) and for the population dynamics of the alfalfa weevil (*44*, Ruesink, in press), its parasitoid, *B. curculionis* (Ruesink, in press) and the Egyptian alfalfa weevil (Gutierrez et al., in press) have been developed and tentatively validated in the field. Coupling of plant, insect, parasite and economic models is at an early stage of development, but results from these efforts have been very promising (*44,45*, Gutierrez et al., in press). Development of optimization techniques for decision-making, embracing cost/benefit analysis is also the most advanced of any of the NSF/IPM projects. Such methods as dynamic programming and projectory decomposition have been used to select optimal single-season tactics for a single grower, such as cutting or spraying the crop (*45–48*). In addition, efforts to develop solutions optimal for a group of growers located within a range of common effect have been investigated (*48*).

To date, implementation of control programs using management models for alfalfa production and pest control has been carried out in two ways. A system of on-line or real-time alfalfa pest management based on survey data taken on weevils and/or crop development in early season and almost current weather from 21 Agricultural Meterological stations in Indiana and 10 first order National Weather Service stations has been developed at Purdue University (*13*). Outputs from this system include plant growth and pest development simulation summaries which provide extension personnel with decision-making information. In an off-line mode, general control recommendations which were model generated and based on past and projected environmental conditions have been used in simplified form by Illinois growers in making pest management decisions (Ruesink, in press).

Soybeans

Soybeans are grown mainly in the midwest and southern U.S. The global importance of this crop is widely recognized. The worldwide shortages of proteins and oils for human consumption became acute in 1974; in the U.S., soybean exports became a major means by which this country was able to restore a more favorable balance of world trade.

In several ways an appraisal of where we stand in management of soybean pests is confronted with difficulty. Unlike cotton, relatively little insecticide is used, but as the increased acreage in the last decades has come mainly in the South where a complex of pest insects is capable of causing significant damage, there has been an intensive campaign by industry to develop extensive insecticide treatment programs for soybean. If this campaign were successful, the situation could follow the same disastrous path which developed for cotton. The research program underway is thus designed to prevent this.

Soybean is unlike cotton also in that there is no single key pest in any region but a complex of threatening pests, and the backlog of biological and ecological knowledge concerning these pests is much less understood. There is evidence that the existence of a complex of predators, parasites, and diseases that attack soybean insects in the South where they are the most threatening is the main reason why no one species has become a key pest. There is also evidence that strains of some pest species are becoming better adapted to feed on soybean, and this applies even in the Midwest where insects have caused little trouble in the past. Consequently, there is at times a real need to use insecticides, and any usage may increase the need for further usage, for it will tend to lessen the effectiveness of natural enemies. Little is known about the effects of soybean insects or diseases on soybean yields or the capacity of the plant to compensate for damage at different stages of the plant's development. Moreover, since most soybean pests are polyphagous feeders on other crops and noncrop vegetation, the relative densities, patterns of distribution, and phenology of these plants affect both pest dynamics (sources, distribution, densities, movement, phenology) and natural enemy effectiveness. Consequently, this complexity makes doubly necessary a systems approach to the problem. This is especially so as the economic threshold for damage by a given species, or a complex of species, will vary during the season with the growth of the plant and with economic developments.

Pest management for soybean has been confronted with both the burden and blessing of being able to mount a coordinated multiple-tactics approach from almost point zero, and in this sense it is much like various crops in developing countries. Only a few years ago soybean insect control in the U.S. essentially was at the single-tactic phase, i.e., chemicals alone were advised if a problem arose, although, depending upon the particular adviser, possible effects on natural enemies were given some consideration. At present, commercial implementation has reached at least the multitactic phase wherein many tactics are used in some regions or states, incorporating also significant biological monitoring, certainly in those areas where "action" or "scouting" programs are used to ascertain need for pesticides. Trends indicate that, even in preliminary programs not significantly utilizing modeling, insecticide usage can be held to half what it would otherwise be, with corresponding increases in profits and improved environmental quality. Costs of scouting can also be reduced by half by using information from recent studies on the phenologies of the pests and the soybean plant and the lack of damage potential except at critical times.

Basic research on several tactics necessary in a systems approach is being conducted. In Illinois a mathematical expression of economic injury levels and data correlating yield decrease with defoliation have confirmed that soybean can (at times) tolerate substantial foliage injury without adverse effects on yield (Ruesink and Carlson, in press). As noted above, resident natural enemies appear to be very important in economical soybean production. A surprising finding is that predators and diseases of soybean insects are much more important than insect parasites. Ways are being studied to make them more useful; a special problem exists with the diseases, as epizootics are triggered only by high humidity and/or heavy dews. Efforts to introduce new natural enemies are being made, especially for the Southern green stinkbug. Varieties exhibiting multiple resistance to several insect pests and diseases are being sought. Starting with lines initially resistant to the Mexican bean beetle, resistance to a number of defoliating insects has been added, e.g., for bean leaf beetle, soybean looper, velvetbean caterpillar and *Heliothis* spp., and lines should soon be commercially available (S. Turnipseed, W. Campbell, and M. Kogan, personal communication).

As information on these tactics is gained, modeling and management and optimization are being explored simultaneously. A broad cooperative effort supported by CSRS-USDA to develop a plant growth model for soybean has been launched. While this is being fully developed scientists at Louisiana State University have formulated a simple model based on records of the progress of soybean development at different dates from planting time. Coupling of insect damage with this rather gross plant model predicts yield to ± 10%. A model framework for corn earworm, velvetbean caterpillar, southern green stinkbug and soybean looper has been developed and it adequately reproduces their development through the season. Lastly, a prototype management model is being developed.

It is too soon to appraise, generally, either the economic or environmental benefits developing from such new programs. One of the most striking benefits is in scientific methodology—the multidisciplinary cooperation that it has engendered. Moreover, as noted above, costs of scouting where scouts are used can be much reduced. Where an insecticide must be used, the amount used has in many areas been reduced by half. It is more difficult to assess just how many acres have not been treated that would have been, except for these new developments. It does seem hopeful that soybean pest control can be prevented from going the way of cotton, whether or not sophisticated modeling has a key role.

Corn

Corn is second to cotton with respect to the total use of pesticides and is one of the most valuable crops (exceeding $12 billion annually) grown in the U.S. Development of integrated control measures for grain corn in the Midwest corn belt of the U.S. has been difficult due to the wide variations in climate and inadequacy of natural control factors in regulating pests of this crop which frequently and sporadically achieve outbreak status. In addition to insecticides, integrated control programs have relied heavily on such measures as host plant resistance, rotation and other cultural measures and intensive monitoring or sampling of pests.

Use of resistant varieties for first generation European corn borers (ECB) and corn leaf aphids contribute significantly to control of these major pests throughout the corn belt (*49,50*). Although the light trap is still considered the best tool for detecting ECB activity, pheromone research has a potential for improved monitoring. Other measures used in integrated control programs are early planting to reduce the potential for development of 15 to 20 insect pests of corn (this treatment increases the damage potential of the ECB), manipulation of irrigation to reduce ECB larval survival, early harvesting to reduce ECB and corn rootworms in succeeding years, and crop rotation which is the best measure for managing corn rootworms (*50*).

With respect to sampling and economic threshold determinations, methods are available for foliage and stalk inhabiting species, but techniques for assessing populations and economic thresholds of the contagiously distributed soil-inhabiting insects, including rootworms, wireworms and cutworms, have been more difficult to develop. The emphasis given to monitoring of corn insect pests is reflected by the six USDA/CES sponsored "pilot" pest management projects which are currently under development in Illinois, Indiana, Iowa, Missouri, Nebraska and Ohio.

Research on modeling for corn pests is at an early stage. Work has been done in forecasting population levels of rootworms based on physical parameters taken from the fields and rootworm samples taken during the previous season, and preliminary models for the black cutworm and ECB are being developed and validated (*51*).

Pine Forests*

Bark beetles are so important in pine forests (our most important coniferous timber type) that all of the NSF/IPM effort has been put on these insects. They are generally the most destructive insect pest on pines, and nearly all major U.S. pine types or regions have a major bark beetle problem—western pine beetle (WPB) in the Pacific states, mountain pine beetle (MPB) in the Intermountain and Rocky Mountain states, and southern pine beetle (SPB) in the South. For the first two bark beetles, extensive blocks of research data have been accumulated for more than 50

*The data on pine forest are taken mostly from Waters (*52*).

years, yet at the initiation of the NSF/IPM project it was felt that the causes of outbreaks and the proper recommendations for their management were still unknown or at least highly controversial. It was necessary that these data be collated and analyzed to elucidate the ecology of bark beetles, the nature and extent of losses, the role of stand age-class and other characteristics, tree species diversity, certain conditions predisposing outbreaks (e.g., disease, fire, wind-throw), and the role of natural enemies and various management tactics.

In these studies researchers do not view their objective as the handing to forest managers of a flat recommendation of what to do about bark beetles. There are many aspects of managing a crop which will not be harvested for 15 to 100 yr that may be affected by a given measure for bark beetle control. Hence, bark beetle specialists expect to develop planning-management advice relative to bark beetles which forest managers would then use in their overall management of the forest. They view as their main objective to obtain an understanding of the role of destructive bark beetles in forest ecosystems and to develop strategies for minimizing the adverse effects of these pests with minimal disruption of the ecosystem and minimal environmental degradation.

Sub-objectives are to develop descriptive and predictive models of the dynamics of bark beetle populations as bases for parameter inputs to stand dynamics and treatment strategies; to develop forest stand growth and development models to include the effects of beetle-caused tree mortality in the context of all destructive agents affecting stand parameters; to develop criteria and analytical models which will permit evaluation of the socioeconomic impacts of bark beetles on forest uses and values; to develop treatment strategies and tactics and models for predicting and evaluating their outcomes, with pertinent information on the costs and environmental safety of these strategies; and to better define the benefits and costs of forest pest management and develop sound methodology for benefit/cost evaluation of the management alternatives for pine bark beetles.

The pine bark beetle ecosystem is complex; it encompasses a wider range of ecological conditions and the space-time dimensions are greater than in most agricultural systems. A pest management system for this ecosystem is even more complex since there is a diversity of social and economic values involved. Over the past few years the participating institutions have developed and refined a model structure of the bark beetle management system (Fig. 1). The primary information flows in the research and development section are shown by the heavy arrows and feedbacks by light arrows. In terms of modeling, both sets of arrows indicate which components provide inputs in some form that are parameters for another.

The four major modeling components are beetle population dynamics, forest stand dynamics, pest impact, and treatment strategies; each is a complex subsystem. The insect population and forest stand dynamics components require basic ecological and biological information to develop the explicit models needed in the pest management system; the impact components require basic ecological and biological information to develop the explicit models needed in the pest management system; the impact component requires the application of economic, social and mathematical theory in order to provide criteria for assessment of potential benefits; and the development of treatment strategies requires a thorough knowledge of ecological and environmental effects of the treatments used. Definition of the system permits refinement of the problem and focuses the research effort. Essential to orderly progression of the work is a thorough knowledge of what is known, and efficient data management systems.

A stand growth model has been developed by the Forest Service, USDA, and this or some modification of it will be coupled with bark beetle population dynamics models. Within-tree population dynamics and stand population dynamics are receiving attention. A study in California on use of the western pine beetle pheromone in assessing beetle attack potential and "confusion" and/or "trapping out" potential is under way.

As an example of what has been accomplished thus far, the following important conclusions have been drawn relative to mountain pine beetle (MPB): beetle epidemics occurred in stands with a high proportion of thick-phloem trees (not all stands with this characteristic support epidemics); qualitative visual classification of tree response 3 weeks after inoculation with *Europhium clavigerum* showed promise for identifying resistant trees (no trees with heavy reactions were killed and trees with light or medium responses were killed at the greatest rate); and important root rots (e.g., *Verticicladiella wagenerii*, *Coniophora putaena and Pythium* sp.) were associated with dead trees, lending support to the hypothesis that root diseases play a role in predisposing lodgepole pine to MPB attack (this relationship has been demonstrated by the western pine beetle group for other species and hosts).

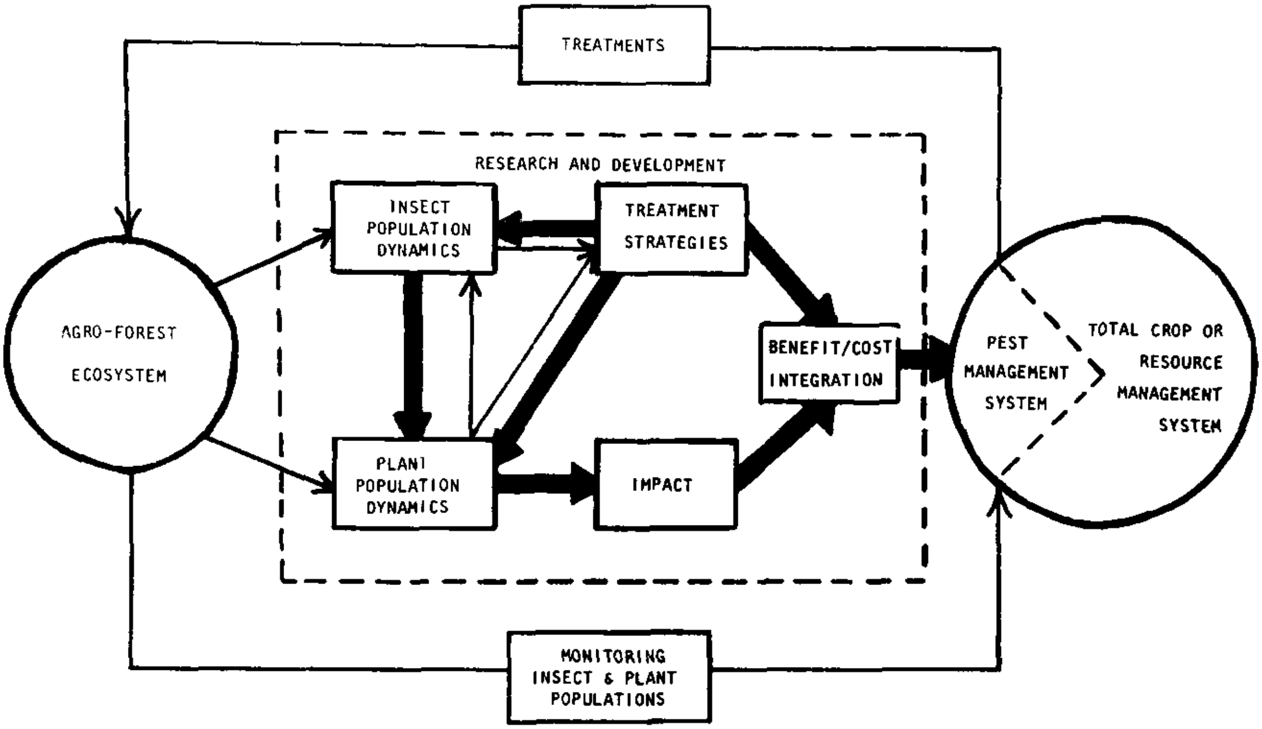

FIGURE 1. Model structure of insect pest management system.

These studies and prior knowledge led to conceptual model of the dynamics of MPB populations. The concepts are summarized as follows: endemic populations are maintained at low levels either by scarcity of thick-phloem trees (in which large numbers of beetles survive and emerge) or by tree resistance — the major regulatory process is competition for food; release to epidemic levels results when resistance in thick-phloem trees is lowered by stresses (e.g. drought, over-stocking, old age, root diseases). The increase in available food results in lower attack densities (per attacked tree), reduced competition, and higher survival and emergence densities. Outbreak momentum is generated by high beetle populations (which apparently can overcome and kill even relatively resistant trees by sheer numbers of attacks. Collapse of epidemics occurs when the larger, thick-phloem trees have been removed from the stand or overall stand resistance increases (predation by insects and woodpeckers may aid population decline.)

A large project along the lines of the NSF/IPM project was initiated this year on the SPB. Economic impact, population dynamics and other work started under the IPM project is being expanded.

One of the toughest problems for the systems analyst in the area of biology is how he can reduce the enormous complexity of biological systems to be able to describe them analytically and yet meaningfully. When the system is reduced to manageable terms, it often no longer represents the real world. Bland Ewing and associates in California have confronted this problem. The space-time dimensions for a bark beetle ecosystem is of the order 10^{14} for area and 10^{10} for time. They have developed a flexible computer language, groups of submodels, and equations and algorithms for computer use by which they can create a simulation which mimics the structure and dynamics of a population of organisms and the behavior of its individuals. By looking at a stand of trees as a system of interlocking clusters, any given cluster can be described quantitatively. The method is being used to model the western pine beetle—root disease relationship. This disease (caused by the fungus *Verticicladiella wagneri*) has been found associated with a high percentage of bark beetle attacked trees. The model will make it possible to test, by simulation experiments, whether the bark beetles in fact may be an instrument in stopping a root disease epiphytotic, and thus beneficial!

Asked what they would be able to recommend for bark beetle management by the end of the project, Waters replied (*52*), "...possibly, (1) use of stand manipulation (cutting treatments, beetle management by pheromones or insecticides, (2) capability of predicting stand dynamics over space and time, (3) capability of predicting outbreaks and (4) liberation of the forester from some erroneous ideas that have constrained his management options."

Cereals

Cereal grains do not receive heavy amounts of pesticide due to the limited number of pests which attack these crops; also the moderate value of the crop on a per acre basis precludes the extensive use of costly pesticides. Cereals, however, are crops of great importance in terms of U.S. food production. For example, wheat, the most valuable cereal is grown on ca. 65 million acres and is valued at approximately $6 billion, annually.

Considerable efforts to develop integrated pest control programs for cereal pests have been made. The principal species to which these programs have been directed include the hessian fly, the wheat stem sawfly, the greenbug and the cereal leaf beetle.

Host plant resistance has played a significant role in development of integrated control tactics against the above species. For the hessian fly and wheat stem sawfly, an estimated 8.5 and 1.5 million acres of wheat, respectively, were planted to resistant varieties in the U.S. during 1969 (*49*). Varieties of wheat resistant to the greenbug are being developed but have not yet been released, whereas several resistant barley varieties are available (*49*). Wheat germ plasm resistant to the cereal leaf beetle, based on leaf pubescence factors, has been identified, and some barley lines show considerable promise, whereas there has been little success with oat varieties (*53*). The total value of research on development of resistant varieties for the hessian fly, wheat stem sawfly and the two noncereal pests, the European corn borer and spotted alfalfa aphid, has been estimated at $3 billion dollars over 10-yr period (*49*).

Considerable success in biological control has been achieved with parasites of the cereal leaf beetle (CLB), of which four or five imported from Europe have been established (*54*). An integrated control system for managing the CLB, including manipulations of their parasites, has been developed (*55–57*). It is based on planting tolerant varieties of oats or wheat, encouraging native natural enemies, such as the spotted ladybird beetle, *Coleomegilla maculata*, establishing the introduced eulophid parasite *Tetrastichus julus*, and the mymarid, *Anaphes flavipes*, treating cereal seeds with propoxur or carbofuran at planting to control the adult beetles so as not to affect the parasites which emerge later, and lastly, if populations of the pest exceed an economic threshold, spraying with carbaryl or malathion.

Considerable efforts have been made to model the population dynamics of the CLB. Gutierrez et al. (*58*) modeled its within-field dynamics on wheat and oats in Indiana, and in Michigan extensive efforts have been made to model its dynamics in relation to its parasites and various host plants, using both a discrete component approach (*59*) and a continuous time model (Lee et al., in press). In addition, the basic elements for an on-line environmental monitoring system for managing this pest have been developed (*8*), and extensive real-time implementation programs are in the early stages of development.

Citrus*

Citrus comprises about 3% of all food consumed in the U.S., and U.S. production of oranges is 36% of world production; that of grapefruit 75%. The national acreage is ca. 1,325,000. This production has been threatened many times by newly invading insect pests and some of them pose continuing problems, in spite of phenomenal success with biological control of a number of species. Insecticides have continued to be widely used, some 11,000,000 lb in 1966. Such use of broad-spectrum insecticides has led to trouble from a number of formerly minor species. The IPM project for citrus was established largely on the assumption that insecticide use could be reduced and sound insect control achieved by using natural enemies and selective, reduced use of insecticides.

From the system analysis viewpoint, the citrus project has perhaps suffered from its blessings; the biological control potential for managing citrus insects seemed so promising that the design of the program was conceived in anticipation of being able to rely on natural enemies, with only minor use of insecticides or acaricides or use only of highly selective types. An experience of ca. 70 years in

*Data on citrus were taken mostly from Riehl (*60*).

California had suggested this possibility for all citrus areas. Biological control certainly offers real potential, sufficient that a number of major pests in citrus growing states may not require treatments or else reduced treatments in major areas. The parasite *Aphytis melinus* appears to be that effective in much of southern California in control of California red scale, and other parasites of purple scale, whereas, for example, *A. melinus* has so far proved incapable of controlling red scale in the San Joaquin Valley; *A. lingnanensis* has been widely colonized in Florida for control of snow scale and is showing much promise. Complete control of purple scale has been achieved in Texas by *A. lepidosaphes* (*61*).

It has also been shown for citrus red mite that the cost of controlling it can be substantially reduced in southern California by low volume application of an acaricide chosen selectively; that generally now in the San Joaquin Valley it is inherently not as damaging as formerly thought and that usually treatments for it can be much reduced because climate, virus disease and predatory mites adequately control it. One of the main insects for which treatments are made, even at times or in areas where insecticides would not otherwise be needed, is the citrus thrips. Damage from this insect (external quality and yield) is presently distinctly important to growers and citrus marketing associations, yet the problem is controversial and subject to assessment. Where *A. melinus* is established, ryania (control efficiency of ca 50%) is the only selective thrips material currently available. Much of the damage is minor and affects the surface of the peel only. Yet, appearance is certainly a marketable quality. The packing industry uses a sliding scale in culling thrips-damaged fruits for the fresh fruit market, depending upon the supply/demand situation, a feature that dismays the systems ecologist trying to develop a management-decision model for citrus insect control.

All this means that management-decision modeling has not gotten under way. The modeling effort in California has been devoted to the population dynamics of California red scale, the key pest, and of its parasites, and presently relating the model to San Joaquin Valley conditions. A model for citrus tree phenology and management of rust mites is being developed in Florida. In Texas, Florida and California, practical systems of integrated control are in operation in some areas. These programs have been initiated without modeling input. While one might deplore the lack of an earlier effort in management-decision modeling, it can be argued that if the snow scale is brought under control in Florida by the parasites the program introduced, the benefits from this alone would dwarf in a few years' time the cost of the entire NSF/IPM project.

Tobacco

Six major classes of tobacco are grown in the United States, largely along the east coast. Flue-cured tobacco makes up 60% of the crop, and North Carolina is the leading grower of this class. In North Carolina a major effort has been made to develop a multidisciplinary integrated approach to control of the insects and diseases (including nematodes) that attack the crop. Rabb et al. (*62*) noted that the use of such teams of scientists well grounded in the relevant basic and applied sciences is the key to progress and necessitates a study of the cropping system as a whole, with attention given to pest populations as system components. Most of the progress made to date has occurred through a very elementary application of systems science and through trial and error. However, the value of the systems approach is realized and advanced techniques of systems analysis are now being researched and offer the potential to further improve the existing system.

The first subsystem the researchers sought to understand was that of the central feature—the tobacco plant and its culture—then the pests, insects and diseases, their economic effects, and the possibilities for reducing those effects.

Historically, preventive or purely intuitive treatments with insecticide have been used on flue-cured tobacco in North Carolina. The growers gradually developed an overestimation of their problems, and insecticides came to be extensively overused and poorly timed. This overuse of such chemicals added unnecessarily to costs, left unnecessary residues on the product, increased personal hazards, contributed to some of the problems and had other adverse environmental consequences.

The goal of the team (*63*) became that of integrating pest control measures with those of crop production to effect economically sound crop protection with a minimum disruption of natural controls and environmental values. The program had two basic objectives: to lower the mean level of pest abundance over a wide geographic area and thus reduce the frequency of outbreaks and to suppress pest outbreaks when they do occur, according to sound economic and ecological principles.

The initial effort (1971) was aimed at the tobacco hornworm and tobacco budworm, but in 1972 tobacco flea beetle and green peach aphid were included, and various tobacco diseases have now been brought in (Rabb et al., in press), with three additional measures added. The methods for insect control consisted of sucker control, early stalk destruction, and applications of selected insecticides only when infestations exceed economic thresholds (using scouting and advising programs). Ellis et. al., (*63*) stated: "The first two practices comprise a diapause control program and serve to lower the mean level of abundance of the key pests. The latter practice allows suppression of pest outbreaks on a field to field basis, but requires frequent field inspection to determine the presence and infestation level of various pests."

The insect monitoring or scouting program, done weekly in 1973, involved 813 farms and 11,350 acres of tobacco. Data on the phase of growth of the crop, the above pest species, and their principal parasites and predators were recorded, with recommendations being made to each grower on the basis of whether densities exceeded economic thresholds: 5 or more fourth or fifth instar hornworms per 50 plants; "heavy infestation" of fleabeetles or aphids.

The sucker control and early stalk destruction (even of nematode-resistant types prone to suckering), *combined with heavy mortality from parasites* and predators, resulted in satisfactory control at reduced cost and reduced natural disturbance and residue problems (always a very sensitive feature in the market). Excessive use of insecticides in the management area in 1973 decreased by 52.9% compared to 1971, the first year of the program. However, there is still room for improvements in the timing and methodology of treatments and the acceptance by growers of the concept of the economic threshold and the need for scouting (Rabb et al, in press).

Changing tobacco markets and cropping practices strongly affect grower acceptance of suggested IPM practices, however. Two important developments have been the elimination of chlorinated hydrocarbons and the wide area adoption of chemical sucker control. Toward the end of the chlorinated hydrocarbon period, the chief motivating interest in IPM by growers was to eliminate undesirable residues from tobacco products—not to reduce costs, not to improve effectiveness of control, and not to protect the environment. They wanted to get top dollar for their tobacco. Now that chlorinated hydrocarbons have been replaced with effective insecticides (including *B. thuringiensis* formulations but chiefly organic phosphates and carbamates) which leave no significant residues, the original motivation for moving to IPM has been reduced. However, there is now less reason for using frequent applications of insecticides for hornworms than prior to the mid-1960's because of uniform adoption by growers of chemical sucker control. This practice was adopted to suppress sucker growth during the preharvest period, but since the material used (maleic hydrazide) acts systemically, it inhibits sucker growth during the postharvest period also. This post-harvest effect is most important to removing food resources for hornworms. Entomologists had tried to reduce overwintering hornworms, but with little success. Ironically, they can take no credit for the success achieved serendipitously by the insertion of chemical sucker control. The increased emphasis on more effective sucker control and earlier crop residue destruction as promoted by "Action" IPM programs has resulted in demonstrated benefits with respect to both insect pests and plant pathogens.

Rabb et al. (in press) warn that while further improvements will surely come from use of systems science, an examination of costs and benefits from this advanced approach show that costs increase with accuracy, and that the benefits also increase but then level off at some point due to diminishing returns. Thus, there is the problem of seeking the practical level of sophistication in methodology *which is financially rewarding.*

Promise of Integrated Pest Management

Many meritorious programs of integrated pest management in other crops are not dealt with here, and the summaries presented in this review are of necessity rather sketchy. This overview should, however, indicate the current status of integrated pest management in the U.S. and provide a basis for speculating on its future promise. We feel that those innovations which are currently being developed (the new), when integrated with essential traditional integrated control elements (the old) (e.g., natural enemies, minimal insecticide use), will provide in the future for significant economic, environmental and social benefits in this country. One might even say that this transition is already in progress and many benefits are now becoming apparent. Of course there is a lag time between research and implementation and by the very nature of research, all of its products will not be used. Yet the evidence suggests that we presently are only beginning to see the outlines of the potential benefits that may be reaped from these developments during the next two decades. The old and the new contain elements of value, and we will do a disservice to society if we do not try to put them together harmoniously.

What integrated pest management programs might look like 10 years hence is a speculative question. It is likely that individual programs for single crops and probably for complexes of associated crops—e.g., cotton, soybeans, and alfalfa—will be developed in response to specific needs, available technologies, and socioeconomic and political factors in the various areas of the country.

Such programs will be implemented in a variety of ways and they will probably replace conventional single component systems of pest control. The speed of their development will vary, for example, with factors such as the uniqueness of the crop and the production system, the economic resources available, and the intensity of the pest problems.

However, a degree of commonality in these programs appears to be developing. The tendency is towards interdisciplinary, multiple component approaches where improved pest monitoring and prediction systems are essential elements and in many cases relatively sophisticated systems science and computer technology will be used; the final delivery message to the producer, however, must be clear and plain, unencumbered with excessive details.

As noted previously, the value of models and the system science approaches which were previously developed with great success in relation to physical systems, remains to be fully tested and evaluated for pest management applications. However, certain benefits from these methods have already been proven. For example, the logic and methodological approach associated with system science has greatly facilitated research, especially in identifying priorities through modeling, sensitivity analysis and validation. With respect to its use in practical management or prediction, the answer is less clear. Much depends upon the weather and our ability to predict it. Many workers, however, who have had experience with these methods are optimistic. Ruesink (in press), in speculating on the progress of integrated pest management programs for alfalfa, has stated: ". . .we have models describing the population dynamics of the alfalfa weevil and *B. curculionis* and a growth model of the alfalfa crop. During the next 2 years, these models will be compared with field data from a wide range of conditions, and refinements will be made as needed. Simultaneously, the technology associated with on-line and off-line utilization of the models will continue to develop. It is our expectation that by 1977 these results will be used to manage the alfalfa weevil on many acres, nationwide. With continued support and encouragement we hope to add models for aphids and leafhoppers towards the end of this decade. By 1980 perhaps we will have the capacity to manage the majority of insect pest problems in alfalfa, based on the use of our model."

If this optimism, which is shared by many others, is correct, there will have to be an intensive period over the next few years of development, validation, simplification, and integration, and then an economic and environmental comparison with traditional methods of development and implementation of pest control. We must remember that trial-and-error experimentation in response to use: need is an essential feedback mechanism which is necessary for improving these systems in response to adapting pests and changing technologies. Furthermore, acceptance and utilization by farmers is really the ultimate test as to the utility of any integrated pest management program. It is certain that many unforseen problems in the area of delivering this type of decision-making information to the grower or pest manager will be encountered. However, we do not see these as insurmountable problems, but more as an exciting challenge which will require the best efforts of our profession.

REFERENCES

1. National Academy of Sciences. Insect-Pest Management and Control NAS-NRC Publ. 1695. National Academy of Sciences, Washington, D.C. 1969.
2. Metcalf, R.L., and Luckmann, W.H. Introduction to Insect Pest Management. Wiley, New York, 1975.
3. Council on Environmental Quality. Integrated Pest Management. U.S. Government Printing Office, Washington, D.C., 1972.
4. Cramer, H.H. Plant protection and world crop production. Pflanzenschutz Nach. 20 524 (1967).
5. Huffaker, C.B. Some ecological roots of pest control. Entomophaga 19:371 (1974).
6. Pickett, A.D. Utilization of native parasites and predators. J. Econ. Entomol. 52:1103 (1959).
7. Michelbacher, A.E. Natural control of insect pests. J. Econ. Entomol. 47:192 (1954).
8. Haynes, D.L., Brandenburg, R.K., and Fisher, D.P. Environmental monitoring network for pest management systems. Environ Entomol. 2:889 (1973).
9. Bowen, H.D., Colwick, R.F., and Batchelder, D.G. Computer simulation of crop production—potential and hazards. Agric. Engineer 54: No. 10,42 (1973).
10. Thomas, J. G. A review of the 1972 cotton pest management program. Summary Proc. 1973 Beltwide Cotton Production Research Conference, 1973. pp. 25–27.
11. Smith, R.F. The new and the old in pest control. Proc. Acad. Nazr. Lincei, 366:21-30 (1968).

12. Kilgore, W.W., and Doutt, R.L. Pest control: biological, physical and selected chemical methods. Academic Press, New York, 1967.
13. Giese, R.L., Peart, R.M., and Huber, R.T. Pest management. Science 187:1045 (1975).
14. Croft, B. A. Tree fruit pest management. In: Introduction to Insect Pest Management. R.L. Metcalf and W.H. Luckmann, Eds., Wiley-Interscience, New York, 1975, pp. 471–507.
15. Smith, R.F., et al. Progress achieved in the implementation of integrated control projects in the USA and tropical countries. OEPP/EPPO Bull. 4: 221 (1974).
16. Casey, J.E., Lacewell, R.D., and Sterling, W. Economic and environmental implications of cotton production under a new cotton pest management system. Texas Agric. Expt. Sta. MP-1152. Texas A & M Univ., College Station, 1974.
17. Beck, S. D., and Maxwell, F. G. Use of plant resistance. In: Theory and Practice of Biological Control. C. B. Huffaker and P. S. Messenger, Eds., Academic Press, New York, Chap. 25, in press.
18. Huffaker, C.B., and Smith, R.F., Eds. Integrated pest management: the principles, strategies and tactics of pest population regulation and control in major crop ecosystems. Progress report and renewal proposal. International Center for Biological Control, Univ. California, Berkeley, 1974.
19. Adkisson, P.L. Cotton subproject director's integrated summary, In: Integrated pest management: the principles, strategies and tactics of pest population regulation and control in major crop ecosystems. Progress report and renewal proposal, Vol. 1., C.B. Huffaker and R.F. Smith, Eds. International Center for Biological Control, Univ. California, Berkeley, 1974.
20. Baldwin, J.L., et al. Bollworm attack on experimental semidwarf cottons. Texas Agric. Expt. Sta. B-1144, Texas A & M Univ., College Station, 1974.
21. Niles, G.A. Adapted short-season varieties and insect control. Western Cotton Producers Conference, Phoenix, Ariz., March 1974.
22. Niles, G.A., Walker, J.K., Jr. and Gannaway, J.R. Breeding for insect resistance. Proc. 1974 Beltwide Cotton Production Research Conference, National Cotton Council, Memphis, Tenn., 1974.
23. Ridgeway, R.L., et al. Programmed releases of parasites and predators for control of *Heliothis* spp. on cotton. Proc. 1973 Beltwide Cotton Production Research Conference, National Cotton Council, Memphis, Tenn., 1973.
24. Duncan, W.G., Baker, D.N., Hasketh, J.D. Simulation of growth and yield in cotton. III. A computer analysis of the nutritional theory. Proc. 1971 Beltwide Cotton Production Research Conference, National Cotton Council, Memphis, Tenn., 1971, p. 78.
25. McKinion, J.M., Jones, J.W., and Hasketh, J.D. Analysis of SIMCOT: nitrogen and growth. Proc. 1974 Beltwide Cotton Production Research Conference, National Cotton Council, Memphis, Tenn., 1974, pp. 117–124.
26. Gutierrez, A.P., et al. An analysis of cotton production in California: a model for Acala cotton and the effects of defoliators on its yields. Environ. Entomol. 4: 125 (1975).
27. Sharpe, P.J.H., and DeMichele, D.W. A morphological and physiological model of the leaf. Trans. Am. Soc. Agric. Eng. (1974).
28. Hall, D.C., and Norgaard, R.B. On the timing and application of pesticides. Am. J. Agric. Econ. 55: 198 (1973).
29. McLaughlin, E.E. The economic threshold and the interface between plant and insect models. Proc. Symp. Application of Systems Methods to Crop Production, Miss. State Univ., June 7–8, 1973.
30. Talpaz, H. Evaluation of economic behavior in an integrated pest management simulation. Proc. 1974 Beltwide Cotton Production Research Conference, National Cotton Council, Memphis, Tenn., 1974, pp. 107–111.
31. Lacewell, R.D., et al. Impact of the Texas High Plains diapause boll weevil control program. Texas Agric. Expt. Sta. MP-1165, Texas A & M Univ., College Station. 1974.
32. Hoyt, S.C., and Caltagirane, L.E. The developing programs of integrated control of pests of apple in Washington and peaches in California. In: Biological Control C.B. Huffaker, Ed., Plenum Press, New York, 1971, pp. 395–421.
33. Croft, B.A. Integrated control of apple mites. Exten. Ser. Bull. E-825, Mich. State Univ., 1975.
34. Croft, B.A. and Brown, A.W.A. Responses of arthropod natural enemies to insecticides. Ann. Rev. Entomol. 20: 285 (1975).
35. Huffaker, C.B., and R.F. Smith, Eds. The principles, strategies and tactics of pest population regulation and control in major crop ecosystems. Integrated summaries (NSF GB-34178), Vol. 1, International Center for Biological Control, Univ. California, Berkeley, 1972.
36. Riedl, H.W. and Croft, B.A. Use of the pheromone trap to quantitatively assess the phenology and density of the codling moth. Proc. 3rd Nat. Ext. Fruit Pest Manag. Workshop. Yakima, Wash. Mar 11-12, 1975, p. 58–67.
37. Falcon, L.A., Pickel, C., and White, J. Computerizing coding moth. Western Fruit Grower, 1976: 8–14 (Jan. 1976).
38. Berryman, A.A., Bogyo, T.P., and Dickman, L.C. Computer simulation of population reduction by release of sterile insects. II. The effects of dynamic survival and multiple mating. IAEA Rept. Vienna, International Atomic Energy Agency 1973 pp. 31–43.
39. Jones, A.L. Principles, strategies and tactics for regulation and control of disease pathogens in the pome and stone fruit ecosystem. Res. Proposal, Mich. State Univ., 1975.
40. Mowry, P.D., Asquith, D., and Bode, W.M. Computer simulations for predicting the number of *Stethorus punctum* needed to control the European red mite in Pennsylvania apple trees. J. Econ. Entomol. 48: 250 (1975).
41. Stern, V.M., et al. The integrated control concept. Hilgardia 29: 81 (1959).
42. Armbrust, E. J., and Gyrisco, G. G. Forage crop insect pest management, In: Introduction to Insect Pest Management, R. L. Metcalf and W. Luckmann, Eds., Wiley-Interscience, New York, 1975, pp. 445–469.
43. Miles, G.E., et al. Simulation of alfalfa growth. Amer. Soc. Agr. Ent. (ASAE) paper 73-4547, 1973.
44. Miles, G.E., et al. Simulation of plant-pest interactions with GASP-IV. Amer. Soc. Agr. Eng. Paper No. 74-4022, 1974.
45. Hildebrand, H.A. The design of an optimal control problem. Proc. N.C. Br. Entomol. Soc. Amer. 29: 49 (1974).
46. Shoemaker, C. Optimization in agriculture pest management II: Formulation of a control model. Math. Biosci. 17: 357 (1973).
47. Shoemaker, C. Optimization in agricultural pest management III: Results and extension of a model. Math. Biosci. 18: 1 (1973).
48. Regev, U., Gutierrez, A.P., and Feder, G. Pest as common property resource: a case study in the control of the alfalfa weevil. Working Paper Series, Dept. Ag. Econ., U. of Calif., Berkeley, 1975.
49. Gallun, R.L., Starks, K.J., and Guthrie, W.D. Plant resistance to insects attacking cereals. Ann. Rev. Entomol. 20: 337 (1975).

50. Huber, R.T. Corn workshop summary. In: Implementing Practical Pest Management Strategies. Proc. Nat. Exten. Insect-pest Management Workshop. Purdue Univ. Mar 14–16, 1972, pp. 116–119.
51. Fairchild, M.L. Bionomics and management of soil arthropod pests. EPA R-302547 1st Ann. Rept., 1974.
52. Waters, W. E. Integrated pest management; the principles, strategies, and tactics of pest population regulation and control in major crop ecosystems. Progress Report and Renewal Proposal, Vol. 1, International Center for Biological Control, Univ. California, Berkeley, 1974.
53. Webster, S.A. Developing resistance to cereal leaf beetle, morphological basis, problems and progress. Proc. N.C. Branch ESA 27: 98 (1972).
54. Stehr, F.W., et al. Establishment in the United States of *Lemophogus curtus* a larval parasitoid of the cereal leaf beetle. Environ. Entomol. 3: 453 (1974).
55. Ruppel, R.F. Velarde, J., and Taylor, S.L. Integrated control of the cereal leaf beetle. Mich. State Univ. Res. Rept. 122: 5 (1970).
56. Stehr, F. W. Establishment in the United States of *Tetrasticus julis*, a larval parasite of the cereal leaf beetle. J. Econ. Entomol. 63: 1968 (1970).
57. Maltby, H.L., Establishment in the United States of *Anaphes flavipes*, an egg parasite of the cereal leaf beetle. J. Econ. Entomol. 64: 693 (1971).
58. Gutierrez, A.P., et al. The within-field dynamics of the cereal leaf beetle (*Oulema melanopus*(L.)) in wheat and oats. J. Anim. Ecol. 43: 627 (1974).
59. Tummala, R.L., Ruesink, W.G., and Haynes, D.L. A discrete component approach to management of the cereal leaf beetle ecosystem. Environ. Entomol. 4: 175 (1975).
60. Riehl, L.A. Integrated pest management: principles, strategies and tactics of pest population regulation and control in major crop ecosystems. Progress Report and Renewal Proposal, Vol. 1, International Center for Biological Control, Univ. California, Berkeley, 1974.
61 Dean, H.A. Complete biological control of *Lepidosaphes beckii* on Texas citrus with *Aphytis lepidosaphes*. Environ. Entomol. 4: 110 (1975).
62. Rabb, R. L., Todd, F.A., and Ellis, H.C. Tobacco pest management. In: Proc. Symp. Pest Management: an Interdisciplinary Approach to Crop Protection. San Francisco, February 1974, AAAS, in press.
63. Ellis, H.E., et al. Tobacco Pest Management, 2nd Ann. Rept., 1972.